AD-A018 042

SOURCE OF INDIVIDUAL DIFFERENCES IN DIGIT SPAN

Don R. Lyons

Oregon University

Prepared for:

Office of Naval Research
Advanced Research Projects Agency

September 1975

ADA018042

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER Technical Report 1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Source of Individual Differences in Digit Span		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Don R. Lyons		8. CONTRACT OR GRANT NUMBER(s) N00014-67-A-0446-0004
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Psychology University of Oregon Eugene, Oregon 97403		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS G1153N, RR 042-06 RR 042-061, NR 154-368
11. CONTROLLING OFFICE NAME AND ADDRESS Personnel and Training Research Programs Office of Naval Research (Code 458) Arlington, Virginia 22217		12. REPORT DATE September, 1975
		13. NUMBER OF PAGES ~~79~~ 85
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Based on a dissertation submitted to the Graduate School,
University of Oregon
Eugene, Oregon

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Individual differences, information processing, digit span

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Individual differences in the ordered recall of list of digits are examined experimentally. The resulting evidence argues that neither differences in rehearsal strategies nor differences in the tendency to group and chunk the digits are major determinants of differences in digit span size. Further experiments attempt to pinpoint the source of individual differences in the sequence of basic information processes hypothesized to underlie performance on the task. The results implicate early processing stages.

Source of Individual Differences in Digit Span

by

Don R. Lyons

This research was supported jointly by:

Office of Naval Research
Psychological Sciences Division
Personnel and Training Research Programs
Contract Authority Number: NR 154-368
Scientific Officers: Dr. Marshall Farr and Dr. Joseph Young

and

Advanced Research Projects Agency
ARPA Order Number: 2284
Amendment no. 3
Program Code Number: 4W10

Contract Number:

N00014-67-A-0446-0004
1 April 1974 - 30 Sept. 1975

Principal Investigator:

Steven W. Keele
Department of Psychology
University of Oregon
Eugene, Oregon
(503) 686-4931

ACKNOWLEDGEMENTS

I wish to thank my adviser, Dr. Steven Keele, for his valuable suggestions and encouragement at every stage in this research. Heartfelt thanks are also due to the other members of my dissertation committee; Dr. Robyn Dawes, Dr. Michael Posner, and Dr. Herbert Prehm; and to Dr. William Chase and Dr. Micheline Chi, for their active interest in this work. I also thank Dr. Chase and Dr. Robert Weber for allowing me to use some of their data.

Invaluable technical assistance for which I am most grateful was provided by: Barbara Lewis, who wrote the computer programs for experiments 1-4; William Ogden, who wrote the programs for experiments 5 and 6; Mary Lyon, who helped analyze data from several experiments; Gayle Moses, who drew the figures herein; and Marcia Stille, who typed the final manuscript.

Funds for subjects and equipment were provided by the Office of Naval Research, contract number N00014-67-A-0446-0004 and NIGMS training grant number 1T01-GM 02165-02.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Intelligence is currently defined by performance on a selected set of tasks. But such a definition is inadequate for those who wish to design environments to enhance cognitive abilities. This venture requires that the designer know more about the mind than the fact that certain kinds of tasks intercorrelate to form factors; with only this information, he or she can do little more than train people on particular tasks and hope for improvement in undefined general cognitive skills. If, however, the common variance in a group of tasks can be traced to individual differences in particular mental processes (whose existence has been suggested by the effects of variables other than individual differences), then the underlying processes themselves, rather than particular tasks which merely reflect their operation, could become the focus for remedial effort.

This dissertation reports an attempt to isolate the mental processes which underly individual differences (ID's) between normal adults in what is perhaps the oldest psychometric measure of intelligence: forward digit span size. Though tests of digit span are nearly as old as scientific psychology itself (Jacobs, 1886), experimentalists and psychometricians have so seldom met on common theoretical ground that no one yet knows exactly what they measure. Binet thought that digit span measured power of concentration, and this view still prevails among some clinicians (Zimmerman & Woo-Sam, 1973). Investigators in other areas of psychology have

different views. Some, like Jensen (1964, 1970), believe that digit span performance reflects an ability to form associations which is probably "closely tied to very basic brain functions". Others (Belmont & Butterfield, 1969, 1971; Ellis, 1970) attribute much of the poor STM performance of retardates to the absence of useful mnemonic strategies, like rehearsal.

The plan of this investigation was to make an explicit and detailed list of possible mnemonic strategies and information processing parameters which might be sources of ID's in span size, and test them systematically. The resulting evidence suggests that mnemonic strategies be eliminated as explanations. Some narrowing of the field of candidate system parameters was also achieved. Among the parameters which remain, presumably, are those responsible for the relationship between digit span and intelligence.

This report is divided into five sections. The first section contains a discussion of the theoretical structure within which the investigation will take place, and a list of strategies and parameters to be examined. The second section provides background information about digit span; the third is a brief discussion of some evidence available on the question at hand. The fourth section describes the expeirments that were conducted, and their results; and the fifth contains concluding remarks.

THEORETICAL APPROACH

The correlation between performance measures on a given pair of tasks does not, by itself, prove anything about the sources of individual differences on them. Two tasks may be highly correlated because ID's on both are caused by the same mental process; or because two different but highly correlated processes are involved. A low correlation between two tasks (assuming reliable measurement) could mean that the tasks do not share a common process or set of processes. But it could also mean that there is a common source of ID's which is obscured by variance due to parts of the tasks which require different processes. In order to disambiguate the meaning of intertask correlations, the tasks must eventually be interpreted with reference to a theoretical structure built from evidence which is independent of the correlational data (Thurstone, 1947).

Experimental psychologists are now engaged in building such a structure, but it is not clear how the as yet incomplete results of their efforts can best be used to understand individual differences in cognition. Hunt, Frost, and Lunneborg (1973) outline a general information processing approach to intelligence, choosing to retain the analogy of the brain as a computing system, with its useful distinction between the structures and elementary processes which describe the system in general and the complex sequences of elementary processes which control most behavior

(control processes). These investigators present convincing arguments and some data which raise the hope that their approach will result in a theoretical understanding of intelligence. But, despite a number of suggestive empirical results, little detailed theoretical analysis seems to have been attempted. For example, Hunt, et al. (1975) showed that subjects with high verbal ability (as assessed on a standard achievement test) did better than low verbals on two different tasks which were designed to measure efficiency of access to overlearned codes. However, as the investigators themselves note, no evidence was sought as to whether ID's in access to codes are mediated by elementary system processes or by control processes (e.g., "...better coding and retrieval schemes"). They also reported that high verbals are more sensitive to the presentation order of speech sounds than are low verbals. But the mechanism underlying these ID's is unspecified beyond the suggestion that high verbals might be more efficient at using internal time tags. Finally, Hunt, et al., showed that verbal ability was related to the speed with which various stages of a complex addition task could be completed. These results were interpreted to mean that high verbals have a general processing speed advantage. But, though each of the stages into which the tasks was analyzed doubtless reflected the operation of some unique control processes, there may exist a particular elementary process common to several stages (and to the reference clerical speed tasks) which could account for the speed advantage. Thus,

there may be no need to assume a general speed factor; further theoretical analysis is required.

The present investigation is intended to represent a more systematic approach to theorizing about cognitive abilities. The theoretical framework which we will be using will be detailed via a list of the mental processes which might be sources of ID's in digit span. Part of this list enumerates mnemonic strategies which might be involved; these are, of course, only a small subset of the mind's store of control processes. However, the sources of span ID's might also be found in characteristics of the parts of the processing system itself; in its elementary processes and structures. To facilitate theorizing at this level, we will suggest a list of the parameters which characterize the basic operations of the mind. We feel that, despite the serious deficiencies that such a list is bound to have, it is a relatively powerful aid to making use of the knowledge that experimentalists have gained.

What follows, then, is a brief description of our working view of the human information processing system. This is not the place to discuss the experimental evidence on which this view is based, since differing interpretations of the evidence have already filled volumes.

Sensory System

We accept the commonly held notion that when a stimulus is

presented, the pattern of activity at the relevant sense organ is analyzed into a set of features which are specific to the presentation modality. The time required for this process will be called analysis time; the internal representatives of features which are activated will be called sensory codes. Such codes could differ between individuals in at least three ways; namely: (a) in the intensity with which the units comprising the code were activated, (b) in the number of units activated (the grain size, or detail level of the code), and (c) in the decay rate of code activation (which could be a function of (a) or (b)). Moreover, there is interference between the codes for successive items which use some of the same sets of units. Such interference is viewed as one major cause of forgetting, and there may be ID's in its severity. Finally, there may be ID's in the activation of images associated with familiar stimuli (for example, the name of a visually presented digit). There is good evidence (Brooks, 1968) that such images occupy some of the same structures as do sensory codes. However, we do not know that the same sources of individual differences govern images and codes. It is conceiveable, for example, that a person whose auditory codes are low in detail could produce rich auditory images. Individuals could also vary in the speed with which they can generate either visual or auditory images. Stimuli must be recognized, however, before associated images can be generated; we now discuss the system which accomplishes this.

Logogen System

After stimulus features have been extracted, an attempt is made to sort them through some sort of discrimination net which compares the features of the given item to those of items with which the system is familiar. The matching of enough features results in the activation of an abstract representation of the item, which Morton (1969) dubbed a logogen. A particular digit logogen, for example, could be activated by visual, auditory, or even tactile stimulation. We assume that logogens are organized together in an associative network; whatever one knows about a given item is associated with its logogen. This includes the information necessary to generate an image of the item. It also includes whatever information is available about the context in which the item was most recently presented.

Even this simple view of the logogen system suggests several parameters which might be sources of ID's. There may be differences between individuals in the efficiency of feature sorting, which might result in faster and/or stronger activation of the correct logogen. There might also be a parameter denoting the sharpness of logogen activation, that is, the degree to which a given item activates its own logogen more than the logogens of similar items. And, like sensory codes, activation of logogens is probably subject to both spontaneous decay and interference due to activation of related logogens; there could be ID's in

parameters characterizing these processes. Finally, we suppose that there are parameters involving the associations to a given logogen. For example, some persons might have a greater number of associations to particular logogens than others; or there may be ID's in the ease with which associations to a logogen are activated.

We assume that the processes which have been posited to this point are automatic; that is, they do not require attention or conscious monitoring. (Evidence relevant to this contention is summarized in Keele (1973) and Posner and Snyder (1975).) Consciousness will, for our purposes, be identified with the contents of a later part of the processing system, called the decision system.

Decision System

One would like to eliminate the need to propose such a system as this for reasons of parsimony. It might be supposed, for example, that the contents of consciousness are just the codes which we have previously defined. But evidence (summarized by Posner and Snyder) indicates that many associations in the logogen system may be active at the same time. So a system which selects the codes which reach consciousness seems required. This system can read and manipulate information from either the logogen system or sensory codes. It can perform any of an unknown number of basic operations on this information, and various sequences

of these operations constitute what we have been calling control processes.

The only parameters of this system which we can define with any confidence are those which govern the reading of information from earlier systems. The speed with which such reading takes place is one such parameter; another might be the speed with which a given place in a network of associations can be accessed to begin readout (Posner, 1973, p. 29). Other relevant parameters might be the sensitivity of the system to code activation, or the criterion level which defines an activated code. We assume that the reading of information from earlier systems underlies all subsequent operations of the decision system.

One such operation is the selection of responses. Since response selection is largely determined by control processes, we will not list parameters of the response system per se; rather, we will mention some aspects of response selection under the heading of strategies. This is not to deny that there are ID's in the basic parameters which characterize the response system; it is just hard to imagine how they could be related to digit span size in a theoretically meaningful way.

So far, we have been considering parameters which describe various processing subsystems. It is also possible, however, that there are ID's in parameters describing general mechanisms which are part of most processing operations. Parameters like the

strength and/or speed of neural conduction; general persistence of activation; or number of units available for processing are examples.

As a final point, it should be noted that the parameters characterizing the system proposed here have numerous interrelationships which hypotheses about digit span ID's must take into account. For example, significant ID's in early processes (e.g., visual analysis) could result in ID's in a later, independently detectable state (e.g., visual code detail), which might in turn affect other parameters (e.g., visual code decay rate) which determine recall performance. In such a situation, to have demonstrated that span size is mediated by visual code decay is not to have explained span ID's; the possibility that earlier processes are producing decay rate differences would have to be investigated.

Mnemonic Strategies

System parameters are by no means the only possible sources of span ID's; ID's in the application of certain control processes may be involved. These processes can be grouped into three classes: rehearsal, coding strategies, and response strategies. Rehearsal processes might underlie digit span ID's if some people devote more attention to active rehearsal of the list than others; this could be reflected in differences in the number of rehearsals performed or in the size of the rehearsal group.

ID's in coding strategies include differences in the tendency

to notice or invent meaningful relationships between presented items, as, for example, when one thinks of successive groups of digits as dates or weights. We refer to such a strategy as chunking, to distinguish it from grouping, which refers to the imposition of a subjective temporal structure on a sequentially presented list, irrespective of the meaning of the groups thus formed. A third coding strategy would be to attempt to generate strong visual or auditory images of the items as they are presented. There may well be ID's in the tendency to produce such images, though the generation of an auditory image of a presented digit is probably automatic in most adults.

At least two response strategies could be sources of span ID's. One is response rate; it is possible that making an effort to read back the digits as fast as possible results in a minimum of memory strength decay. It is also possible, of course, that the important determinants of ID's in response rate are not the subjects' intentions, but their abilities. A second response strategy that could improve recall is to pause and rehearse the list before responding, thus making it less susceptible to subsequent interference.

Summary

Table 1 summarizes the theoretical structure which we have outlined here, so that easy reference can be made to it in subsequent discussions. We are now prepared to examine the literature on digit span itself.

Table 1

Possible Sources of ID's in Digit Span Size

I. Individual differences in consciously applied mnemonic strategies.

A. Differential rehearsal

1. Presence vs. absence of rehearsal

2. Differences in number of rehearsals

3. Differences in size of rehearsal groups

B. Differential coding of the digit list

1. Differences in tendency to form meaningful chunks; to notice or invent relationships between items.

2. Differences in grouping structure imposed on list

a. size of group used
b. definiteness of grouping, strength of group

3. Differences in tendency to generate detailed visual or auditory images

C. Differential response strategies.

1. Response rate--faster responses might allow less decay

2. Pause time before response initiation--a longer pause might allow better fixation and less response interference

II. Individual differences in information processing parameters.

A. Sensory and image system

1. Visual analysis time (time to create visual code)

2. Auditory analysis time

3. Visual code activation strength or detail

4. Auditory code activation strength or detail

5. Visual code decay rate

6. Auditory code decay rate

7. Amount of interference within visual anlaysis pathways caused by successively coded items

8. Amount of interference within auditory analysis pathways

9. Generated visual image activation strength or detail

10. Generated auditory image activation strength or detail

11. Auditory image generation speed

12. Visual image generation speed

B. Logogen system--contains abstract codes accessible through different sensory pathways

1. Speed of activation of correct logogen

2. Strength of logogen activation

3. Sharpness of logogen activation, that is, the degree to which a given digit activates its own logogen more than it activates the logogens for other digits

4. Decay rate of logogen activation

5. Degree of mutual interference or inhibition between activated logogens

6. Number of existing associations to digit logogens

7. Ease of activation of associations

C. Decision system--manipulates sensory or logogen system codes

1. Reading rate through logogens or codes

2. Speed of access to the codes to be read

3. Sensitivity

4. Criterion

D. Response system--discussed under strategies

E. General parameters

1. Neural conduction speed

2. Neural conduction strength, leakage

3. General activation decay rate

4. Number of functional units in projection and analysis space

BACKGROUND INFORMATION

The focal task of this investigation is as follows: the subject receives a list of unrelated single digits at the rate of one item per second, immediately after which he attempts to repeat the entire list in order from memory. Then the list length is increased by one, and the process is repeated. The longest list length at which the subject can repeat the list without error (or some roughly equivalent measure) is taken to be his digit span.

There are numerous variations of this task; standard procedure on the Weschler Adult Intelligence Scale (WAIS) uses spoken digits and includes a backwards recall condition. Here, we will be concerned only with recall in the original order. Moreover, we will use visual presentation, as this facilitates precise temporal control of the presentation conditions, and it is well established (Brener, 1940; Jensen, 1964, 1971) that visual and auditory presentation share the same sources of variance. In fact, evidence to be discussed in detail later (Brener, 1940; MacKenzie, 1971) demonstrates that the digit span test taps a general memory span ability, one which accounts for almost all of the variance in immediate serial recall performance with a variety of materials and using either mode of presentation.

Early History

According to Blankenship (1938), the limited size of immediate

memory span and individual differences therein was discussed as early as 1870 by Oliver Wendell Holmes, though no formal experiments were conducted. The first reported experiments are those of Jacobs (1887) and Galton (1887). Jacobs set a number of precedents in his brief article: he suggested the term 'span' to refer to the largest number of items correctly repeated. He elected to use digits instead of letters or nonsense syllables for testing, apparently because he feared that prior associations derived from reading would reduce span size for letters. Finally, he established a uniform presentation procedure which, with minor modifications, is still being used.

Jacobs discovered that memory span size increases with age in children, and that the best students had the highest spans. Galton expanded these findings by demonstrating that institutionalized retardates, even 'savants' with extraordinarily detailed memory for well rehearsed material, had small spans.

The relationship between memory span and intelligence was again investigated by Bolton (1891) on data from 1500 school children. Bolton argued that memory span tests "...do not apply to the retentiveness of the memory. They may be considered as tests of concentrated and sustained attention." Unfortunately, he gives no reasons other than "my own experience and observations upon the pupils" for this conclusion. Nevertheless, this view was shared by Binet. Wolf (1973) discussed Binet's attempt (in L'Etude Experimentale de L'intelligece) to tease apart separate faculties

of memory and attention in experiments performed upon his two daughters. Binet concluded that memory for lists of digits is "uniquely a test of voluntary attention", which was viewed as an important component of intelligence. Memory for digits was thus placed in the first of Binet and Simon's intelligence tests (the 1905 scale), and there it remained through all subsequent revisions in France and America.

<u>Relationship to Intelligence and Age</u>

Today, psychometricians view digit span (as assessed on the WAIS) as one of the poorer measures of intelligence at the high end of the scale, but an "extremely good" test at the low end (Matarazzo, 1972). Table 2 shows the raw intercorrelations of Digit Span with other subtests of the WAIS. These intercorrelations are lower, on the average, than those of the other verbal subtests, but the reliability of Digit Span is also relatively low (.66 for ages 25-54). Jensen (1970) reported that the correlation between Digit Span and full scale WAIS IQ (minus Digit Span) is .75 after correction for attenuation. Exactly how much the Digits Backward portion of the test contributes to this relationship is apparently not known. Incidentally, the heritability of Digit Span appears to be only moderately high: Pezzulo, Thorsen, and Madaus (1972) reported an H^2 of .55 for a sample of 37 fraternal and 28 identical twin pairs.

Table 2

Correlations between Digit Span and other subtests of the WAIS, for a sample of 355 persons, aged 25-36.

From Matarazzo, 1972, p. 237

	Information	Comprehension	Arithmetic	Similiarities
Digit Span	.53	.40	.49	.51
	Digit Symbol	Picture Completion	Block Design	Picture Arrangement
Digit Span	.41	.39	.39	.47
	Object Assmebly			
Digit Span	.30			

Forward digit span in adults exhibits a slight but significant decline with age. From a peak of 6-8 in the late teens, it drops about eight percent over the next forty years (Gilber, 1941). However, much of this mean decrement may be due to the imminence of death in some persons (Reimanis & Green, 1971). Children's digit spans are considerably smaller than those of adults. However, Chi (1974) has presented evidence that if stimuli of equal familiarity to children and adults (pictures of familiar faces) are used, and if children are given longer presentation times than adults to compensate for their relatively slower naming time, memory spans of adults and children are about the same size (that is, between three and four

faces). How span size differences due to development, aging and IQ are related is an important question to which the results of the present investigation might be applied.

SOME RELEVANT EVIDENCE

Relatively few studies have been specifically directed toward the question at hand, but perhaps thousands of investigations involving memory span or similar short-term memory measures might be relevant. Since an exhaustive consideration of these is impossible, the strategy adopted here was to sample selectively from several research areas.

Factor Analytic Studies

There are two general questions one might ask with regard to factor analytic work with memory span: (1) Do various measures of memory span yield a single common factor, or a number of specific factors? And (2), What abilities does memory span have in common with other measures of memory performance? Factor studies have yielded a clear answer to the first question, but not to the second.

Brener (1940) provided considerable evidence for the existence of a single general memory span factor. He assessed span size for various kinds of stimuli with both visual and auditory presentation, and generally found high intercorrelations. Some examples are given in Table 3. These data strongly suggest that immediate memory for lists comprised of unrelated items is not either a modality-specific or an item-specific ability. This has several implications for the set of hypotheses presented earlier.

The finding of high correlations between types of material

Table 3

Intercorrelations of Measures of Memory Span

Using Different Materials and Presentation Modalities

(After Brener, 1940)

	1 Digits	2 Consonants (visual)	3 Colors	4 Designs	5 Consonants (oral)	6 Words
1 Digits (visual)	—[a]					
2 Consonants (visual)	.88	—				
3 Colors (visual)	.71	.86	—			
4 Geometric Designs (visual)	.74	.80	.85	—		
5 Consonants (oral)	.86	.87	.77	.74	—	
6 Concrete Words (oral)	.73	.75	.70	.62	.82	—

[a]reliabilities were not reported

eliminates explanations based on differential familiarity with digits. It is unlikely that digit span would have survived for three quarters of a century as a component of intelligence tests if this were what it measured, but formal confirmation is reassuring. The digit familiarity hypothesis is represented in our outline by parameter II B 5, number of associations to digit logogens. Actually, other digit-specific parameters (digit recognition time, etc.) could have been placed throughout the list and then eliminated, but this example is sufficient. Associational explanations that remain rest on more general parameters like II B 6, associational fluency; or II E 5, available analysis space.

Brener's demonstration of a high correlation between visual and auditory presentation conditions was replicated by Jensen (1964, 1971), who argued that this result ruled out the existence of modality-specific immediate memory abilities for vision and audition. However, neither Brener's nor Jensen's presentation rate (one item/two seconds, and one item/second, respectively) was fast enough to prevent the subject from generating the auditory image corresponding to the name of each stimulus, in the visual presentation condition. There is, therefore, no evidence that the modality of the memory code which mediated recall wasn't auditory in both cases. If the term "visual memory" refers to more than just the presentation modality, then this experiment is not an adequate search for visual memory ability.

Nevertheless, the finding can be used to eliminate a few

parameters on our list from further consideration. It is clear that ID's in visual and auditory stimulus analysis time (II A 1,2) cannot be involved. And it is also unlikely that the process of generating an auditory image from visual input is a source of ID's if it is granted that this process uses different pathways than auditory stimulus analysis. ID's in the shared pathways are, of course, still candidates.

Another important factor analysis was reported by MacKenzie (1971). He analyzed fourteen different tests of immediate memory and identified both a large common factor and a smaller factor specific to those tests in which stimuli were presented simultaneously instead of serially. Tests with the highest loading on the major factor included the standard memory span task with digits and letters, repeated digit span (in which a sequence was presented three times in succession before recall), probe-digit recall (Waugh & Norman, 1965) and running memory span (Pollack, et al., 1959). Tests with lower but still substantial loadings were span tests with simultaneous presentation, and letter recognition. Unfortunately, neither details of the presentation procedures nor the intercorrelations and reliabilities of the tests were reported. Nevertheless, some of these results are suggestive. For example, the running memory span task was originally designed to discourage active rehearsal and grouping of the items by making the length of the presented sequence unpredictable and requiring recall of only the last few items. If this manipulation succeeded for MacKenzie's subjects, then the fact that this test loaded highly on the span

factor would indicate that active strategies are not responsible for the individual differences that this factor represents. However, since Hockey (1973) showed that the optimum strategy on this task interacts with presentation rate, this result must remain only suggestive.

The studies reviewed so far show that a large number of serial recall tasks share a common ability. The fair-sized loading of the letter recognition task on MacKenzie's span factor suggests that this ability may be even more general. However, a search for a confirmation of this hypothesis through other factor studies of memory is not encouraging. Anastasi (1930) lists thirty-two early studies from which few firm conclusions can be drawn because of various methodological difficulties. For our purposes, the most serious of these difficulties is that the reliabilities of tests were rarely reported, and those that were given were generally low. This makes the typically low (.10-.30) reported correlations between various memory tasks difficult to interpret. Anastasi's own correlational study of visual immediate memory used tasks of moderate to high reliability (.53-91) and considerable variety. She found that forward digit span was poorly correlated with various paired associate and recognition tasks (mean r=.107). However, in all tasks except digit span, each to-be-remembered item was presented for three seconds. It is therefore possible that between-subjects differences in performance on these tasks was due to differences in the selection of mnemonic strategies, strategies

which may not have been applicable to the digit span task. It is conceivable that if such strategy variance were controlled, a larger general memory ability might emerge. In general, subsequent investigations have shown similar mediocre correlations between span tasks and more complex ones (French, 1951; Kelley, 1964; Guilford & Hoepfner, 1971), and they are subject to the same interpretation. For our purposes, it is not sufficient to know that span tasks do not generally correlate highly with other kinds of memory tasks; we need to know if there exist controlled situations under which high correlations are obtained. If a high correlation is observed between performance on two tasks after strategy variance has been eliminated, then the remaining ID's on the tasks may have a common source.

Clinical Studies of Distraction and Anxiety

Binet's belief that digit span measured the ability to focus attention has received some study, but little support in the clinical literature. A search by Frank (1964) through a variety of relevant studies resulted in no convincing evidence for the notion, in his view. For example, Guertin (1959) found that neither intermittent nor continuous distracting sounds (including a clearly audible conversation) disrupted digit span performance, and Craddick and Grossman (1962) reported the same result for visual distraction. However, Allen (1962) argued that the most important source of distraction may arise within the subject; anxiety was

given as an example. A number of studies (Moldowsky & Moldowsky, 1952; Walker & Spence, 1964; Pyke & Agnew, 1963; Hodges and Spielberger, 1969; Knox & Grippaldi, 1970) have found that situational (state) anxiety results in a lowered digit span score. Some of these studies have also shown an effect of trait anxiety, as measured by the Taylor Manifest Anxiety Scale, while others failed to find such an effect. The effects of trait anxiety are generally presented as rather small differences in group means, suggesting a weak relationship. Walker and Spence reported correlations, but the highest of them (.26) was in the wrong direction for the anxiety-produced deficit theory. Thus, though anxiety may well effect some people's spans, there is no evidence that differences in habitual anxiety level are a primary determinant of span differences. Moreover, the effects of anxiety are not necessarily due to internal distraction. Pyke and Agnew mention the possible involvement of reduced range of cue utilization under arousal, as proposed by Easterbrook (1959); perhaps attention is <u>too</u> focused when one is anxious, and consequently, contextual cues which would aid retrieval are not encoded. There is evidence that other forms of arousal can decrease digit span, for example, studies by Blankenship (1938) found that digit span is larger in the morning than in the afternoon, though arousal level is generally lower in the morning (Luce, 1974). This result was confirmed more recently by Blake (1965) and Baddeley, Hatter, Scott, and Snashall (1970). None of this, of course, provides any

evidence that individual differences are mediated by arousal.

Research with Retardates

Ellis (1963) proposed that the short-term memory deficits typically found in retardates stems from an impoverished stimulus trace, manifested in both subnormal acquisition and greater than normal memory decay rate. The decay rate portion of this hypothesis has not fared well, according to a review by Belmont and Butterfield (1969). Moreover, Ellis and others (Ellis, 1970; Belmont & Butterfield, 1971, 1973; Brown, 1974) have more recently come to emphasize the role of mnemonic strategies in explaining retardate memory performance. There are several lines of evidence which establish that retardates engage in much less spontaneous rehearsal than do normal adults: Ellis (1970) showed that the slower the rate of presentation in a kind of probe memory task, the better the performance on the primacy portion of the serial position curve, for normal adults. Retardates did not benefit from the slower rate, and they reported rehearsing far less than did normals. Moreover, he showed that instructing normals not to rehearse reduced their performance, largely in the first eight of twelve serial positions. Anders (1971), using the same task, introduced a delay between list presentation and probe, and found that preventing rehearsal by filling the delay interval hurt the performance of normals more than that of retardates. And, Belmont and Butterfield (1969, 1971) measured

pause times in a task in which the subject initiated the presentation of each successive stimulus. They found that normal subjects paused for increasingly longer times as they got further into the to-be-remembered list, but retardates did not. The normal pause time pattern was said to reflect the increased rehearsal load with each additional item.

Evidence is available that retardates lack other mnemonic strategies in other tasks. Prehm (1968) reviewed studies of paired associate learning which show that retardates use fewer complex mediational strategies in such tasks than do normals. He also cited clustering experiments which show that retardates are less likely to use semantic clusters. Spitz (1968) demonstrated that grouping digits by twos on a forward digit span task aided retardates more than normal children, who presumably initiate grouping on their own. Brown (1974) reviews more recent evidence in the same vein.

Notwithstanding the research it has inspired, the view that retardate memory deficiencies can best be described as a lack of mnemonic strategies has some troubling aspects. It is not at all clear that retardates can do as well as normals on many memory tasks even if strategies are controlled. For example, results presented by Belmont and Butterfield (1971b), Figure 8, p. 245, show the effect of forcing retardates and normals to rehearse during a self-paced six-item probe task. Forced rehearsal helped both groups, but it did not decrease the spread

between them much.

Moreover, the strategies which retardates have thus far been shown to lack are not general learning strategies, but specific aids to coping with episodic memory tasks (Tulving, 1972; Prehm, 1970). Meaningful material is not usually learned via rehearsal or the conscious selection of mnemonics; most everyday learning is probably a relatively effortless byproduct of comprehension (Norman, 1975). Thus, extended training of retardates in rehearsal strategies and the like (Brown, 1974) seems unlikely to produce general improvements in learning ability. Strategy deficits in retardates are probably not the result of lack of prior training; normal adult siblings of retardates who were raised at home would undoubtedly be found to rehearse, for example. It is a safe bet that knowledge of the underlying reasons why retardates do not tend to select efficient control processes will ultimately be of far greater usefulness than the fact itself.

One investigator who continues to espouse a basic processes theory of retardate memory is Jensen (1970). As noted earlier, Jensen has argued that digit span performance reflects an ability to form associations, a certain amount of which is necessary but not sufficient for a normal IQ. However, for our purposes, the most relevant of Jensen's experimental work has dealt with digit span ID's in normals, and it will therefore be discussed in the next section.

Experimental and Physiolcgical Evidence

Jensen (1964) conducted a number of studies of memory span ID's in a search for a general interference factor in both span and serial learning tasks. He found little common variance in either the two sorts of tasks or in his various measures of interference, and he argued that digit span performance is comprised of three different abilities: (1) strength of initial stimulus registration, (2) speed of trace consolidation, and (3) susceptibility to interference with consolidation. This is by no means the only interpretation of his experimental evidence, however, as we will show.

Jensen conducted three major experiments with span tasks besides his examination of visual versus auditory presentation, which has already been discussed. The experiment which appears to be the cornerstone of his theory examined individual differences in proactive and retroactive interference. In this experiment, the subject got one sequence of from four to seven (visually presented) digits, and then a second one, followed by an instruction to recall either the first or the second list. Control conditions involving just one list in either the first or the second position were included. Written serial recall was required, and the score was the proportion of digits in their correct serial position. The result was that recall scores on the first list were correlated only .28 with scores on the second, yet the reliability of each measure was about .60. Jensen's interpretation was that proactive

and retroactive interference affect different processing parameters. Proactive interference, he speculated, might operate by preventing strong initial registration of subsequent material, while retroactive interference disrupts consolidation of traces which have already been formed. Unfortunately, he presented no converging evidence for this interesting idea. He also took the results of this experiment as evidence that two or more different abilities contribute to the variance in digit span performance. But this is not a necessary inference; instead of interacting with two hypothetical components of digit span variance, RI and PI conditions might simply be adding unique variance. This would water down the correlation between conditions without implying anything about the components of the digit span task by itself. There is some evidence that this is in fact what happened. On the first day of the task, variance in the PI condition was nearly twice as large as that of the control condition (immediate recall without PI); on the second day, this ratio increased to over three to one. These differences are significant ($p<.001$, $dF=102$) via a t-test for variance differences between correlated samples (Ferguson, 1971). One source of such added variance could be differential attention strategies. Jensen discusses the possibility that subjects, being unable to remember both lists, simply abandoned the effort and began concentrating attention on one list or the other. He presents several arguments against this explanation, but admits that it cannot be ruled out. However, even if some

more fundamental explanation for the low correlation between PI and RI is correct, the result does not necessarily imply much about the source of digit span ID's.

Jensen's other two experiments with span tasks also yield striking results, some of which are difficult to interpret theoretically. In one of these, he correlated scores for immediate recall with recall after a 10-second interval. The interval was filled by requiring subjects to respond selectively with key pressing to a series of pluses and minuses, one item per second. This may not have been sufficient to prevent some people from rehearsing, but the experiment was also done with lists of colored forms for which rehearsal was probably more difficult. The correlation between immediate and delayed scores was .79 for digits, and .88 for the forms. Jensen argued that these correlations (together with a very small subjects by delay interaction) imply that the delay interval introduces a new source of ID's. But this effect is not very large, and it could have been introduced by differential tendencies to rehearse during the delay, especially with digits. It seems to me more important that the delay, which reduced the mean number of items recalled by 26%, had so little effect on individual differences. This result is evidence against hypotheses based on ID's in the rate of decay of either image codes or activated logogens, if one supposes that activation of such codes is still decaying several seconds after their formation. If such an assumption is not made, then some other process must be proposed to

explain the detrimental effect of delay.

In another experiment, subjects were given lists of five to twelve digits, followed by either a signal to recall immediately or a signal to wait for a second presentation of the same list, which was then recalled. The resulting correlation between immediate recall performance and performance after repetition was .91. Variances in the two conditions were almost equal and there was a small subjects x conditions interaction. Repetition increased mean recall by 19%. This result appears to be most relevant to hypotheses which posit ID's in the initial code strength or logogen activation level which results from the presentation of a stimulus (II A 3,4; II B 2). If the initial presentation of a digit results in greater activation of the corresponding codes in some persons than in others, then, by one line of reasoning, a repetition of the digit ought to increase this activation difference and, hence, the observed variance in recall performance. No such increase was observed. However, the theory requires only the postulation of a low ceiling on activation level to reverse this prediction. No interaction at all is difficult for either version to explain.

Two final general points about Jensen's work are relevant. From a methodological standpoint, it should be noted that in this series of experiments, Jensen substituted proportion of digits correctly recalled for the standard criterion based on the correct repetition of whole lists. Evidence to be presented later indicates that these two measures are not perfectly correlated, and may

involve somewhat different sources of ID's. The second point to be made is that Jensen may not still hold the theory of digit span ID's discussed here. His recent discussions have not gone into detail about what underlies digit span ability.

To summarize: Jensen's experiments, in my view, have not presented convincing evidence for any theory of digit span ID's, though they suggest the elimination of a few of the parameters under consideration. We have not discussed in detail Jensen's attempts to relate memory span to serial learning and other tasks, because little resulted from these attempts which is of interest here.

However, one of Jensen's incidental results may be relevant: a correlation of -.39 was reported between digit span score and the time required to read the words on an uncolored control card in the Stroop task. Recently, Baddeley, Thompson, and Buchanan (1974) reported an even higher correlation (-.638) between the time a subject required to read a list of words and his memory span for those words.

The rate at which an adult can read words could be a function of any of several processing parameters: visual anlaysis time (II a 1), sorting time for the logogen system (II B 1), time required for the decision system to make use of logogen system information (II C 1-4), or response execution time (I C 1). Visual analysis time has already been eliminated as a source of digit span ID's by the high correlation between visual and auditory

presentation. But there is little evidence available on ID's in the other parameters.

In this connection, two EEG studies linking digit span to temporal properties of the brain should be mentioned. Saunders (1961) reported a correlation of .40 (N=29) between occipital alpha frequency and a difference score reflecting the degree to which a subject's WAIS digit span was above or below the level predicted by his scores on the other subtests. He also reported that if dominant EEG frequencies outside the alpha range are included, the correlation is even higher. And Shucard and Horn (1972) found a correlation of .26 between span for a list of letters and latency of the P_3 component of the visual evoked potential. Significant but generally smaller correlations with other evoked potential components were found in the same subject sample, which consisted of 108 persons aged 16 to 68. There is, at present, no good theoretical explanation of either of these results.

Summary of Evidence

Factor analytic studies of memory have demonstrated that there exists a general memory span ability for various kinds of material and presentation conditions, and that this ability is tapped by the digit span task. Thus, most code-specific or material-specific parameters cannot be major sources of digit span ID's though structures common to auditory codes and auditory

images could still be involved. Clinical studies have provided no evidence for the traditional belief that the test is primarily a measure of either distractibility or anxiety. Recent research with retardates implicates lack of efficient mnemonic strategies, especially rehearsal, as a source of deficient STM performance, though it was argued here that such explanations are likely to be inadequate in the long run. Finally, experimental studies provided evidence against hypotheses based on differential trace decay, and some evidence for a processing speed theory; other interesting results were difficult to interpret.

In the next section, experiments which explore a number of these leads are described.

EXPERIMENTS

Experiment 1

Experiment one was designed to test the hypothesis, encountered in the literature on retardate memory, that ID's in rehearsal strategies (I A 1-3) underlie ID's in span size. Lists of digits were presented (visually) to a single group of subjects at both the standard one digit per second presentation rate and at a much faster rate exacted not to allow rehearsal. If ID's at the standard rate are due to rehearsal strategies, then the effect of the fast rate ought to be to either eliminate these ID's (greatly reducing the between-subjects variance) or reorder them (disrupting the correlation between conditions). If the correlation between slow and fast presentation is high, and if the variances in the two conditions are of comparable size, then the same source is probably responsible for ID's at both rates, and this source cannot be rehearsal strategies.

Subjects. Nineteen paid subjects (ten women, nine men) were obtained from a subject pool at the University of Oregon. All had vision correctable to normal and normal hearing. Ages ranged from nineteen to thirty-nine years. Because neither age nor sex were significantly related to memory span size in this sample, these variables were not analyzed further.

Method. Subjects were presented with lists of ten single digits via a computer-controlled oscilloscope display system.

The digits were randomly generated, with the restriction that no pairs of digits normally adjacent in either ascending or descending order could be adjacent in the lists; this eliminated easily remembered runs. An experimental trial consisted of the following events: (a) the subject initiated a trial by pressing a microswitch; (b) a sequence of ten digits was presented; and (c) the subject attempted to write down the digits in order on a response sheet containing a box for each digit. Subjects were told that only digits recalled in their proper serial position would be considered correct, and a bonus of ½¢ per correct digit and 5¢ extra per completely correct sequence was given. Moreover, a standard recall order was required: a subject had to start at the first position on the response sheet and either write the first digit there or draw a line through the box before proceeding. Recall was to be continued in strict serial order, and the experimenter was present to assure that this instruction was obeyed. Subjects were allowed to guess if they had some idea what might have been presented, but to avoid completely random guesses.

Two list presentation rates were used. In the slow (1 digit/second) rate, each digit was presented for 250 msec, and then a dot mask was exposed for 10 msec; during the remaining 740 msec before the next digit, the screen was blank. In the fast rate condition (3 digits/second), the digit and mask presentation times were the same as for the slow rate, but the period between the offset of the mask and the onset of the next digit was reduced from 740 to 70 msec. Since alphanumeric material takes about

250 msec/item to rehearse after it has been read into memory (Chase, 1974), no rehearsal between successive items is possible at this fast rate.

Each subject was tested for two half-hour sessions. The first session consisted of two 10-trial blocks at the slow rate followed by two blocks at the fast rate; in the second session, the fast rate blocks were presented first.

Results and Discussion. The proportion of digits recalled in their correct serial position was computed for each subject in each condition. Individual differences on the task were large--proportions correct ranged from .223 to .781 at the slow rate and from .168 to .732 at the fast rate. The fast rate reduced mean proportion correct from .586 to .436. This reduction is significant (t_D=6.65, p<.001).

As would be expected if the two presentation rates tap the same ability, the correlation between them was high (r=.82). Correction for attenuation using the between-sessions correlations as test reliabilities ($\sqrt{r_{35}r_{55}}$=.86) increases the correlation to .95.[1] Moreover, the variance at the fast rate was not reduced.

These results argue strongly against the role of rehearsal strategies in producing ID's in this task. The next experiment links these results to a more standard measure of digit span.

Experiment 2

Subjects. Seventeen of the subjects from experiment one were available for testing and use in this analysis. Six additional subjects from the same subject pool were tested for use in subsequent experiments.

Method. The physical setup was the same as in experiment one. The procedure used to measure digit span differed from the standard one in the use of visual instead of auditory presentation, and in the inclusion of a greater number of digit lists (ten of each length, instead of two). In each of two half-hour sessions on separate days, subjects worked through five ascending series of lists of four to twelve digits, presented at the one digit/second rate. Subjects were required to attempt all lists of a series, and no feedback was provided until the end of the session. Credit was given only for lists which were reproduced without error, and this was made clear to the subjects. Requiring subjects to attempt lists of all lengths, while another departure from the WAIS procedure, allows the use of Brener's (1940) scoring method. In this method, the longest list length for which all ten lists were reproduced correctly is found. Then, the proportion of lists reproduced correctly on each of the longer lists is added to this basic span size. For example, if a subject got all ten of the six-digit lists, six of the seven-digit lists, two of the eight-digit lists, and none of the longer lists correct, his span size would be: $6.0 + 0.6 + 0.2 = 6.8$.

<u>Results and Discussion</u>. Reliable individual differences were found. Performance on the two sessions was correlated .91; hence, the reliability of the overall measure is estimated to be .95 via the Spearman-Brown formula (Guilford, 1954). Span sizes over all twenty-three subjects tested ranged from 5.0 to 9.4, with a mean of 7.3 and a median of 7.1. There was no apparent facilitative effect of having been in experiment one, as the seventeen subjects from this experiment had a mean span of 7.3, while the mean span of the six new subjects was 7.5.

To test the rehearsal strategy hypothesis, the subjects from experiment one were divided at the median into 'high-span' and 'low span' groups. The high group contained the scores of eight subjects, and the low group had seven. The scores of two subjects were at the median, and were therefore not used. The mean span size for the high group was 8.3; for the low group, it was 6.1. This represents a separation of 1.8 times the standard deviation of the entire group. Figure 1 shows the mean proportion correct in each of the conditions of experiment one, for each of these groups. If the reason for the superiority of the high span group lies in differences in rehearsal strategies, then the elimination of rehearsal with fast presentation ought to bring the groups closer together. There is no hint of such an effect.

To the extent that other mnemonic strategies require time to execute, this result argues against their involvement also.

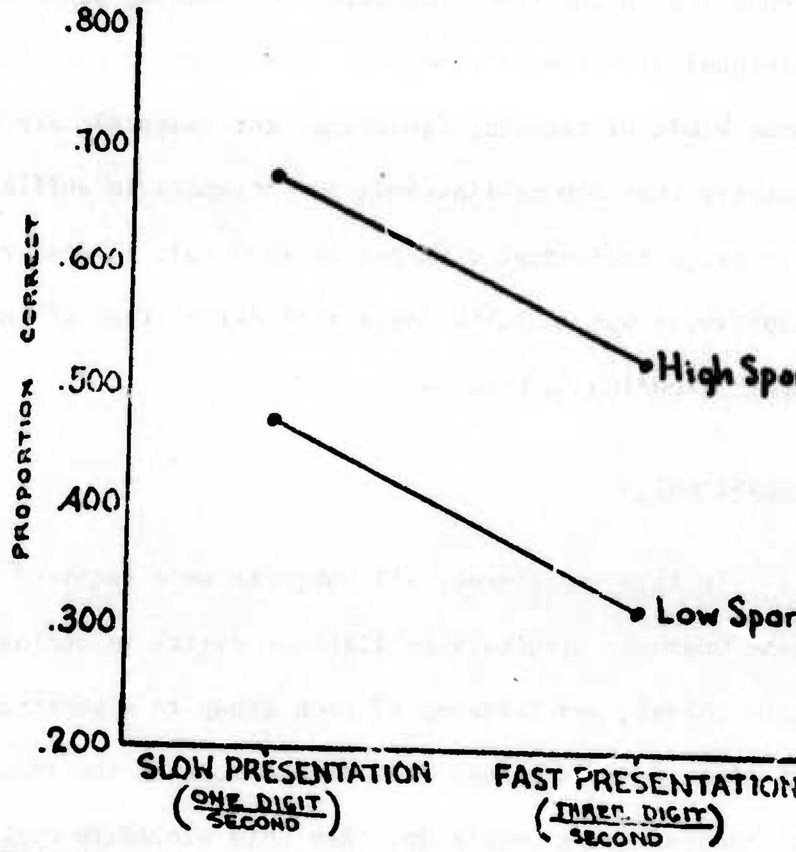

FIGURE 1: Mean proportion of digits correctly recalled in Experiment 1 for groups of subjects with high and low digit spans.

For example, chunking is a time-dependent process (Kleinberg & Kaufman, 1971), and therefore if individual differences are based on ability or propensity to chunk the digits (I B 1), a drastic reduction in the time available for chunking ought to reduce individual differences somewhat. Some might argue, however, that some kinds of recoding (grouping, for example), are performed so quickly that 330 milliseconds per stimulus is sufficient time for large individual differences to occur. Therefore, the next experiment was conducted as a more direct test of the role of other recoding strategies.

Experiment 3

In this experiment, all subjects were required to impose the same mnemonic structure on lists of digits (grouping the digits into threes, and thinking of each group as a three-digit number). If digit span ID's stem from differences in the amount and kind of restructuring people do, then this procedure ought to result in some reduction in span size variance.

Subjects. The seventeen subjects from experiment one were used.

Method. Each subject memorized lists of twelve digits for immediate written recall. There were three different experimental conditions. In condition UGR (ungrouped), the twelve digits were presented at the rate of one digit per second (250 msec stimulus duration; 750 msec ISI), and only standard (experiment one)

instructions were given. In condition GRU (grouped, unvoiced), digits were presented at the same average rate, but were temporally segregated into groups of three by placing a larger inter-stimulus interval after every third digit, so that the sequence of ISI's was: 580, 580, 1160; 580, 580, 1160; etc. In addition, each subject's response sheet was divided into four groups of three positions each by conspicuous black bars, and he was instructed to "think of each group of three digits as a three-digit number, and try to remember them that way". In the third condition (grouped and voiced--GRV), subjects grouped the digits as above, but were also required to read each three-digit number aloud during the intergroup intervals. This condition was actually run before the unvoiced condition to ascertain that everyone understood and were obeying the grouping and chunking requirements. As in experiment one, subjects were required to recall in strict serial order, and bonuses were paid.

Results and Discussion. Mean, range, and variance of scores in each condition and intercorrelations between conditions are given in Table 4. The experimental manipulation succeeded in improving recall on the average, since mean performance in the grouping-and-chunking conditions significantly exceeded that in the ungrouped condition ($p<.01$). But ID's on the task were hardly affected, at least in the unvoiced experimental condition: the UGR-GRU correlation is high, and the reduction in variance with forced grouping is insignificantly small. Further

Table 4

Summary Statistics and Intercorrelations of Recall Scores for Each Condition of Experiment 3. Diagonal Entries in the Correlation Matrix are Split-Half Reliabilities. All Correlations Are Significant, $p < .01$

SUMMARY STATISTICS

Condition	Proportion Correct Mean	Range	Variance
UGR	.538	.236-.733	.01736
GRU	.288	.293-.759	.01498
GRV	.576	.217-.742	.02146

INTERCORRELATIONS

	UGR	GRU	GRV
UGR	.950		
GRU	.842	.94	
GRV	.60	.73	.95

confirmation was obtained by plotting performance on this task as a function of digit span, as assessed in experiment two. The results, for both the unvoiced and voiced groups, are shown in Figure 2; the high and low span groups contain the same subjects as in experiment two. It is clear that forced grouping and chunking produces no convergence of the two groups. Figure 2 also suggests that voicing the digits does not interact with digit

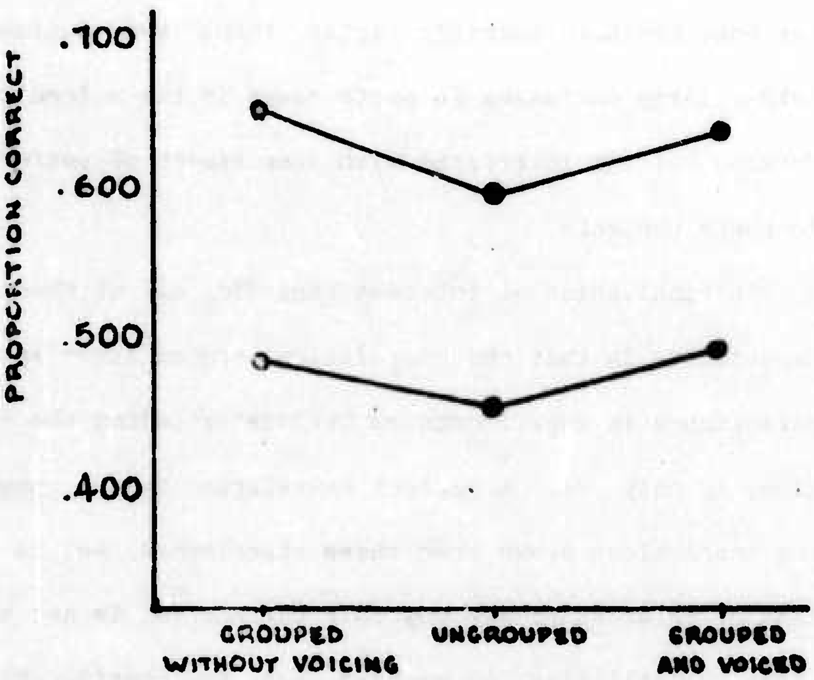

FIGURE 2: Mean proportion of digits correctly recalled in each condition of Exp.3, for groups of subjects with high and low digit spans.

span performance, though it apparently interacts with performance on the written recall task. The evidence for this is that the UGR-GRV correlation is significantly smaller than the UGR-GRU correlation ($t=2.30$, $p<.05$). This might be taken as evidence for some auditory-specific factor, though some subjects experienced rather large decreases in performance in the voiced condition. Perhaps voicing interfered with some aspect of performing the task in these subjects.

A final point of interest regarding all of these first three experiments is that the correlation between digit span and overall performance in experiments one to three (excluding the voiced condition) is only .71. A perfect correlation is not required for the conclusions drawn from these experiments, but it is nevertheless of interest to ask why this correlation is not higher. (Test reliabilities, as we have seen, are considerably higher than .7.) A likely answer is that the digit span task forces the subject to concentrate on the entire list, while the written recall task allows focussing on a manageable subset of the list and ignoring the rest. Four subjects mentioned using this strategy when asked how they performed the task, and all four had relatively higher scores on the written task than on the digit span test. The correlation between the two tasks for the remaining 13 subjects is .82.

Experiment 4

The outline of hypotheses with which we are working contains one group of strategy-based explanations which has not yet been tested. These are hypotheses which posit ID's in organizing and outputting responses. Experiment four employs a recognition task which does not require extensive response organization, so a response organization theory of digit span ID's would not predict a high correlation between span and recognition performance. A low correlation between these tasks might, however, have another implication. Many of the basic memory system parameters on our outline govern the quality of item information in memory, and it is this information which is tapped by the recognition task. A low correlation could imply that ID's in memory span have little to do with memory for the digits themselves, but only for their order. There is already some evidence (Estes, 1972; Dornic, 1975) that the processes underlying the storage of item and order information are not the same. As was pointed out earlier, many low recognition-recall correlations already exist in the literature, but these might have been caused by subjects' use of different strategies on the two tasks. The goal here is to see if a high correlation can be obtained by controlling for such attenuating factors.

Subjects. Twenty-one of the twnety-three subjects whose digit spans were assessed in experiment two were available for use in this experiment.

Method. Subjects were given a target list of twelve letters, sequentially presented, and followed by a probe letter. They responded with a keypress denoting whether or not they thought the probe had been presented in the target list (left forefinger, yes; right forefinger, no). Letters were used instead of digits because the digit set is too small to provide enough distractors. A target set of six Gibson figures was tried in pilot work, but some subjects hit upon the rather successful strategy of paying attention to only a portion of each figure. Pilot studies also indicated that the presentation rate of the target list is crucial: when the standard one-per-second rate was used, some subjects (not necessarily those with the largest digit spans) were able to find word associates to 'meaningless' letter sequences. On the other hand, when the very fast (3/second) presentation rate used in experiment one was tried, some subjects claimed that they could not read all of the letters. The following event timing was finally settled upon: each target letter was presented for 250 msec, followed by a 150 msec inter-stimulus interval. The probe followed the offset of the last target letter by one second, and remained on the screen for two seconds. Subjects were instructed to wait for the offset of the probe before responding. This helped to reduce differences in speed/accuracy criteria which had been evident in pilot studies. Subjects were further instructed not to voice or whisper any of the letters to aid recall.

The experiment consisted of two one-hour sessions, a total of 500 trials per subject. A bonus of 1¢ was paid for each correct trial.

Results and Discussion. The correlation between the overall proportion of correct responses in the recognition task and digit span size was .63. The two sessions of this task correlated .79, yielding an estimated whole-test reliability of .88. The recognition-digit span correlation rises to .69 when corrected for attenuation.

Analysis of the components of the recognition task in terms of individual differences yields additional information. Table 5 shows the intercorrelations of various scores derived from this task, and the correlation of each with digit span.

Two major points are evident from Table 6. The first is that performance with negative probes is nearly uncorrelated with performance on positive probe trials, and only the latter is significantly related to digit span. At present, we have no satisfactory explanation for this. Since errors on negative trials are false recognitions, one might argue that performance on these trials is largely a function of the subject's criterion for deciding that a letter has been recognized, while performance on positive trials is a function of both criterion and memory strength. However, the correlation between memory span and d', which is often regarded as a pure measure of memory strength, is only .58; apparently nothing is gained by removing criterion variance.

Table 5

Intercorrelations of Various Components of Recognition Performance, Experiment 4. Positive Trials Are Those in Which the Probe Letter Was Presented in the Target List; Negative Trials Are Those in Which it Was Not. Reliabilities, Derived From Between-Sessions Correlations, Are in the Diagonals.

	1 Total	2 Positive	3 Negative	4 First Eight	5 Last Four	6 Digit Span
1. Total Proportion Correct (P(C))	(.88)					
2. P(C) For Positive Trials	.74*	(.84)				
3. P(C) For Negative Trials	.81*	.21	(.88)			
4. P(C) For the First Eight Serial Positions (Positive Trials)	.63*	.96*	.08	(.85)		
5. P(C) For the Last Four Serial Positions (Positive Trials)	.71*	.59*	.53*	.37*	(.72)	
6. Digit Span	.63*	.65*	.20	.58*	.42*	(.95)

* Indicates a significant positive correlation, $p<.05$, one-tailed

The second interesting finding is that a fairly reliable score is derivable from performance on just the last four serial positions of the positive trials. Considering its lower reliability, this score appears to correlate about as highly with digit span as does performance on the first eight serial positions. Apparently,

at least some of the processes responsible for digit span ID's are common to both primary and secondary memory (Waugh & Norman, 1965).

But the main question raised by this experiment is: does the failure to get a digit span-recognition correlation as high as test reliabilities allow reflect sampling error and/or unanticipated sources of error variance, or does it mean that there is more than one major source of ID variance in digit span performance? Sampling variability alone is unlikely to have introduced a bogus factor, since, even after the correlation is corrected for attenuation, the upper bound of its 95% confidence interval is .87. Thus, the absolute maximum amount of the variance of a perfectly reliable digit span test predictable from a perfectly reliable version of this probe task is estimated to be 75%, leaving room for at least a small additional factor. However, there may have been uncontrolled sources of variance. One possibility is that there were differential practice effects due to the fact that six of the subjects had not done experiments one and three. However, the data reveal no such effect: the mean probe score for the experienced group was .765; for the inexperienced group it was .769. Another possibility is that the precautions taken to minimize any speed-accuracy tradeoff were a failure, but there is no evidence for this either. Reaction times for positive and negative trials correlated .98, so an overall reaction time was computed. It correlated -.02 with performance on positive trials,

-.15 with negative, and -.11 with overall performance. (The correlation with digit span was +.23.)

Perhaps the most likely possible sources of uncontrolled variance are ID's associated with various peripheral features of the recognition task. In this regard, suspicion falls on the use of letters instead of digits and the fast presentation rate. Though these variables have been shown to have little effect on digit span ID's, they might affect ID's in a probe task. It therefore seems unwise to take this correlation as proof of the existence of two or more factors in digit span performance. Rather, independent evidence for such separate factors will be sought in the next two experiments.

The remaining experiments reported here are analyses, in terms of individual differences, of data from studies designed by William Chase and Robert Weber to examine the speeds of various mental processes. Chase and Weber kindly agreed to run subjects whose digit spans were known, and to allow me to use their data. Their analyses of these experiments, however, may not agree with the one presented here.

Experiment 5

In the first four experiments, performance was measured by the number of correct responses, with little regard for the speed with which these responses were given. But the fair-sized correlation between memory span and reading rate for word lists

(Baddeley, et al., 1974) suggests that there may be a speed factor underlying span size. In an earlier discussion, it was noted that the source of this correlation could be the speed of any of a number of component processes, from stimulus analysis to response execution. It is possible to dichotomize these into 'early' and 'late' processes, with the division being made at the output from memory. Thus, early processes might be the extraction of features from the visual input and the automatic sorting of these features, resulting in the activation of an internal representative of the item. Later processes might include readout of active items by the decision system, and selection and execution of the appropriate responses. Note that consciousness, which we have identified with the operation of the decision system until a better theory is offered, probably come late in the processing sequence, and therefore the effect of variation in choice of strategies (and, perhaps, also in motivation level) ought to be reflected by the speed of the later processes.

Experiment five is an attempt to separate early and late processes, and to examine the relationship between the speed of the latter and digit span. The idea was to measure the rate at which short, easily remembered lists can be read out from memory once they have been placed there. This can be viewed as a measure of the speed of the decision and response system components of reading, if it can be shown that the list is firmly in memory for

every subject, so that ID's in readout rate are not determined by the ID's in the retrievability of the list. This readout rate might be crucial in determining memory span performance, since a faster rate might allow less memory trace decay to occur. If individual differences on this measure correlate well with digit span but not with recognition performance, this interpretation would be supported. This is because recognition performance is assumed to be the more direct measure of the strength of the list items in memory; if readout rate were to correlate highly with performance on both tasks, it could be argued that readout rate was being determined by memory strength. Another possible result is that readout rate correlates poorly with both tasks. This would suggest that the source of the correlation between memory span and reading speed is not to be found in decision and response processes.

Subjects. Nineteen of the subjects from the previous experiments were used; recognition scores were available for only eighteen of these.

Method. A list of three, four, five, or six capital letters arranged in a horizontal row was presented. (Lists were drawn randomly from either a set of visually confusable letters, a set of auditorilly confusable ones, or a neutral set; however, not enough data was available to examine ID's as a function of confusability, so results from the three sets were pooled.) When the subject had committed the list to memory, he pressed a key;

the list disappeared; and he received an instruction to rehearse the list either aloud or silently. The list was rehearsed three times on each trial, with a keypress after each rehearsal to time it. Subjects were instructed to rehearse as fast as possible, but no bonus was paid. Twenty practice trials were given, followed by 36 experimental trials (108 rehearsals) under each condition. (Aloud and silent trials were randomly interspersed with two other tasks which are not relevant here.)

Results and Discussion. Figure 3 shows the function relating mean list rehearsal time to list length for high and low span subjects (nine in each group). The marked curvilinearity introduced by the times for the longer lists reflects the fact that lists near the memory span take disproportionately longer to rehearse than do smaller lists (Chase, 1974). This upswing is probably caused by difficulties in remembering the lists, and therefore if the slope of the entire list length function is taken to measure readout rate, a correlation with both digit span and recognition score ought to exist for this reason alone. The data confirm this: the slope of the aloud rehearsal trials correlates −.48 with memory span, and −.49 with recognition performance. (Correlations with the silent rehearsal slope are in the same direction, but smaller. It appears that aloud and silent conditions tap somewhat different processes in addition to a common factor, as the correlation between them is .40. Since it includes the overt response, the aloud condition is a better reflection

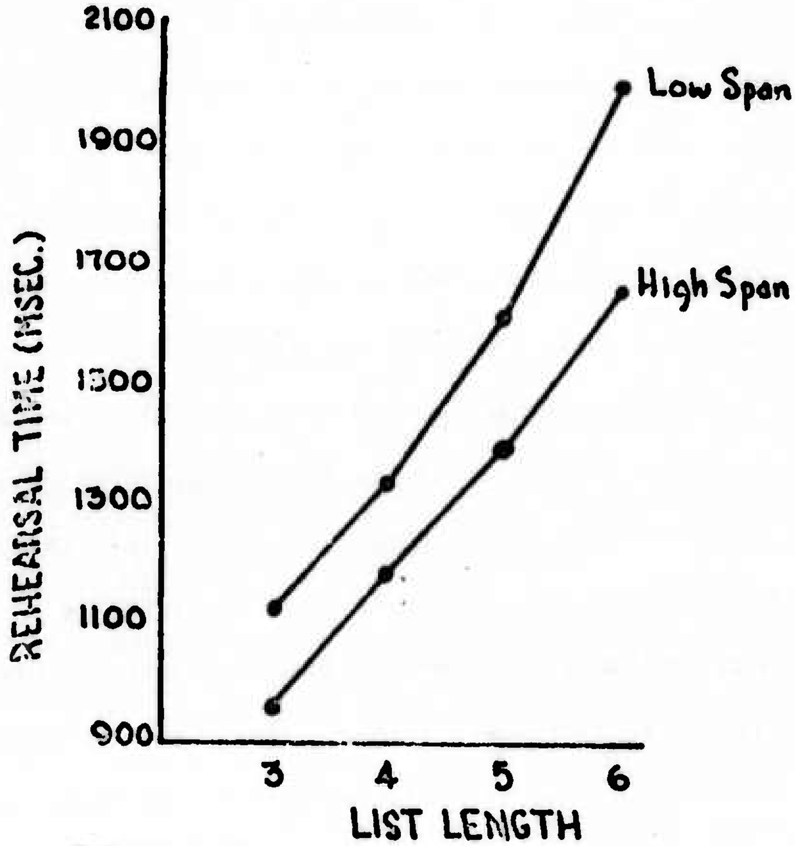

FIGURE 3: Time to rehearse a list as a function of list length for subjects with high and low digit spans. Exp. 5.

of the processes of interest here.)

A fair examination of the role of readout rate itself requires that only easily remembered lists be considered. Another glance at Figure 3 shows that the reaction time difference between high and low span groups does not increase from lists of three to lists of four letters. An increase would be expected if readout rate and memory span were related in the hypothesized manner. This negative result was verified by correlational analysis, as follows.

A relatively pure measure of readout rate for easily remembered lists was derived by simply subtracting each subject's mean time to rehearse three-letter lists from his time to rehearse four-letter lists, in each condition. The intercorrelations of these scores with digit span and recognition performance are given in Table 6.[2] For comparison, the mean reaction times for three-letter lists and a difference score based on times for lists of five and six items have been included in the analysis.

The main point is clear from the correlations in line six of the table: readout rate from easily remembered lists appears to be unrelated to digit span. Those who distrust the derived score will note that the raw reaction times predict span size a little better, but not well enough. The difference score based on the longer lists (6-5) _is_ correlated with both span and recognition scores, as would be expected if this score reflected ID's in memory for the lists.

Table 6

Intercorrelations, Experiment 5

	1 Aloud Readout Rate	2 Silent Readout Rate	3 Mean Readout Rate	4 6-5 Mean	5 RT Three-Letter Lists	6 Digit Span
1 Readout Rate (Aloud)						
2 Readout Rate (Silent)	.21					
3 Readout Rate Mean	.70*	.85*				
4 Mean Diff: Length 6 Minus Length 5	.35	.53*	.58*			
5 Mean Time, List L Length 3	.16	.21	.21	.56*		
6 Digit Span	-.01	-.06	-.04	-.46*	-.20	
7 Recognition Score[a] (Exp. 4)	-.24	-.18	-.26	-.51*	-.11	.59*

[a]Based on eighteen subjects (otherwise, N=19)

*Significant p<.05, two-tailed

Given the instability of correlations with so few subjects, a replication of this experiment would be desirable. Fortunately, data are available from another experiment, designed by William Chase, in which a somewhat different procedure is used. In this study, subjects were given a short, sequentially presented list of numbers, and were allowed several seconds to rehearse them silently. Then an instruction asking for either silent or aloud rehearsal was given; the subject rehearsed the list five times; and then he pressed a timing switch. Immediately following this, the other of the two instructions was given, and the subject rehearsed the list five more times. Seventeen subjects in this experiment had had digit spans assessed, and fifteen of them had been in the rehearsal study just discussed.

The results obtained with this procedure are very similar to the previous ones in the aspects of importance here. Figure 4 shows the list length function obtained, and again there is no interaction between span size and rehearsal rate for lists of three or four items. Table 7 lists the same correlations that were computed for the earlier data.[3] With the exception of the correlations with silent rehearsal rate (and with the means based partially on this rate), this table demonstrates about the same relationships as the last one; the pattern of correlations with digit span, in particular, confirms the original results. And for the fifteen subjects who were in both experiments, the correlation between mean readout rates as measured by the two

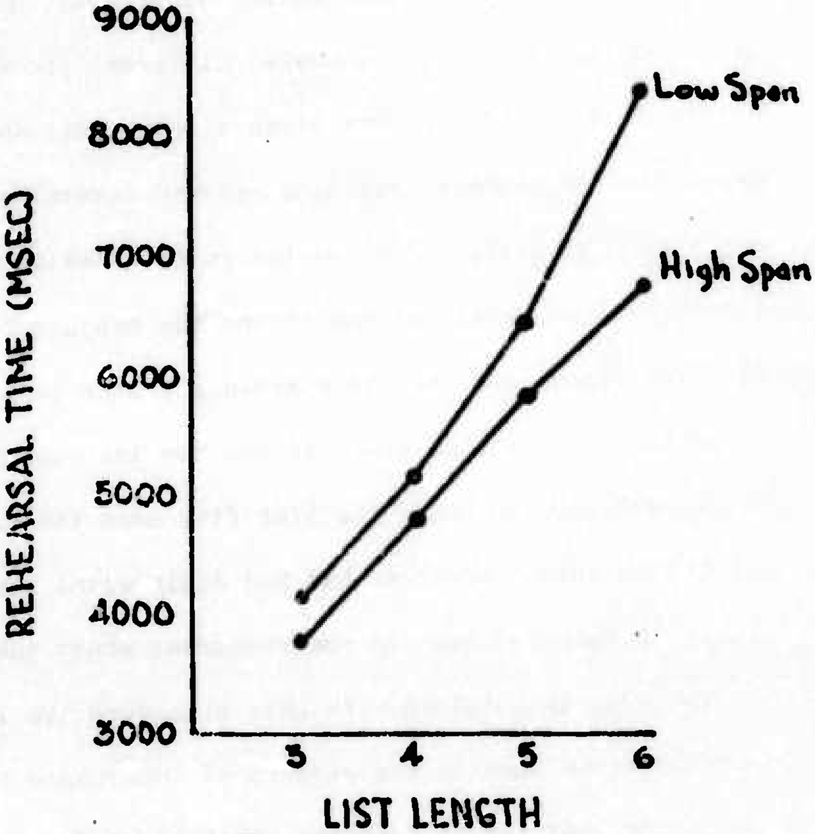

FIGURE 4: Time to rehearse a list five times, as a function of list length, for subjects with high and low digit spans. Exp.5 (replication).

Table 7

Intercorrelations, Replication of Experiment 5

	1 Aloud	2 Silent	3 Mean	4 6-5	5 RT	6 Digit Span
1 Aloud Readout Rate						
2 Silent Readout Rate	.28					
3 Mean Readout Rate	.73*	.86*				
4 6-5 Mean	-.17	.56*	.18			
5 RT Three-Letter Lists	.42	.08	.34	.16		
6 Digit Span	-.02	-.21	-.13	-.34	-.22	
7 Recognition Score[a]	-.04	-.45	-.21	-.47	-.03	.66*

N=17, except [a]N=16

*Significant, p<.05, two-tailed

different procedures was .58. If these scores are averaged, the resulting measure, based on 308 rehearsals per subject, correlates only .04 with digit span. These findings eliminate readout from memory as a possible source of digit span ID's.

Experiment 6

In experiment five, it was assumed that readout from memory was the memory management operation most likely to be related to memory span size. In this experiment (also based on Chase and Weber's data), the relationship between digit span and other operations on material in memory is examined. Further negative results would strengthen the notion that the major sources of memory span ID's are earlier in the processing sequence.

Subjects. Same as in experiment five.

Method. Subjects were given a version of the metered memory search task (Weber & Blagowski, 1970). In this task, a list of four, five, or six capital letters is presented. The subject commits these to memory, and then he receives (visually) an instruction consisting of a starting point (one of the letters in the list) and a step number (an integer from one to three). The subject must then respond with the letter which is the requested number of letters in the list away from the starting letter (reading left to right). If the right end of the list is reached before the requested number of steps have been executed, the count continues with the leftmost letter. For example, if

the target list were XPFAQ and the instruction were " 2 A ", the answer required would be "X". As the subject spoke his answer, a voice-key was triggered, determining his reaction time, and the correct answer was displayed on the screen. If the subject was incorrect, the trial was discarded. Twenty practice and 162 experimental trials were given during a single one-hour session.

Results and Discussion. Reaction time in this task is expressible by the following equation:

$$RT = B_0 + nB_1 + mB_2$$

where n is the list length; B_1 is the rate at which the time to locate the starting item increases with list length; m is the number of steps required; B_2 is the time per step; and B_0 is a constant representing the time required for all processes *except* locating the starting item and stepping through the list. The parameter B_2 cannot be identified with any single parameter on our list, since the stepping operation involves not only reading each item from memory but also keeping track of the number of steps one has gone through. Given the evidence from experiment five that readout rate and memory span are uncorrelated, a high correlation between B_2 and span size might implicate the involvement of this "keeping track" operation. However, the obtained correlation was low ($r=-.17$).[4] Moreover, the correlation with recognition performance was also small ($r=-.16$). The B_1 parameter probably also represents a relatively complex mental operation; locating an item might involve retrieval of

information about the item itself as well as something about its context. Since the ability to retrieve item information is measured by performance on the recognition task, it is heartening to find a moderate (but nevertheless insignificant) correlation between B_1 and recognition score (r=-.36). However, there is no correlation (r=-.06) between B_1 and memory span.

The last parameter (B_0) presents a different correlational picture. It correlates modestly with digit span (r=-.36), but its correlation with the recognition task is small and in the opposite direction (r=.13). This could easily have been a chance result, but further analysis suggests that it represents a genuine and interesting pattern of relationships.

It turns out that B_0 is not a very good measure of anything in these data. It has a strong negative correlation (r=-.67) with B_1, for the following reason: to the degree that there is error in the measurement of a slope, the slope and intercept will tend to be negatively correlated. The correlation between B_0 and the stepping rate (B_2) could well have been due to such error (r=-.20). However, this contribution of B_2 to B_0 was obtained by extrapolating back one step, from the time required for one stepping operation to the time that should be required for none. But the contribution of B_1 is an extrapolation back from a list size of four to a hypothetical list size of zero. Thus, whatever error exists in measuring the slope will be magnified fourfold in the intercept, resulting in theoretical

absurdities like negative intercepts (of which there were several in these data). Thus, the degree to which B_0 reflects the speed of input and output processes is swamped by the degree to which it measures error in B_1. Note that this is not a criticism of Chase and Weber's design, since they were not concerned with analyzing B_0. But we will presently show that if less pure (but less error-ridden) estimates of what B_0 is supposed to be measuring are examined, a strong relationship with digit span which is relatively independent of recognition performance is uncovered.

If an 'intercept' parameter is computed by extrapolating B_1 backward only one step instead of four (and collapsing over all step sizes), the resulting scores correlate -.65 with memory span, and only -.19 with recognition performance. Eliminating the extrapolation completely by using the observed mean reaction time for all lists of four letters yields correlations of -.66 and -.27 with span and recognition scores. These reaction times are impure estimates of the real B_0 in two ways: (1) they include the average overall stepping time; and (2) they include the time required to locate the starting item in lists of four letters. However, it is easy to show that neither of these impurities is responsible for the large correlation with digit span. First, stepping time (B_2) has already been shown to be unrelated to either digit span or recognition performance. Second, the rate at which the starting letter is located (B_1) was shown earlier to be related more strongly to recognition performance

than to digit span, and there is no theoretical reason to expect the opposite result. In fact, contamination of the reaction times by B_1 may be causing what little correlation there is between these times and recognition score. If the mean reaction times for lists of six letters (which are contaminated to a greater degree by B_1) are examined, the correlation with digit span goes down to -.60, and the correlation with recognition performance increases to -.40. Finally, and perhaps most convincingly, the mean time for lists of four letters is correlated only .15 with B_1. This correlation increases to .55 for lists of six letters, as expected.

Why should this reaction time correlate with digit span? Experiment five showed that response processes are unlikely sources for such a correlation, and we have just argued that neither B_1 nor B_2 are involved. The relatively low correlation with recognition performance suggests that ID's in memory for the lists are not the common factor (though it is probably wise not to eliminate this possibility entirely). This leaves ID's in reading the instructions and preparing to carry them out, a task which could involve practically any subprocesses. The result is therefore probably unanalyzeable, but tantalizing nevertheless.

CONCLUSION

The foregoing experiments have provided rather conclusive evidence against the involvement of mnemonic strategies in producing ID's in digit span. The high correlation between memory for digits presented at the standard rate and at a rate too fast to allow much rehearsal (experiment one) weighs against explanations based on differences in rehearsal strategy. Forced grouping and chunking of the digits improved recall, but it did not do so differentially across subjects with high and low spans (experiment three); thus, ID's in the use of these mnemonics are not the basis of span ability, at least in our sample of normal young adults. This is not to say, of course, that great amounts of practice in such techniques cannot lead to large digit spans. Hunt and Love (1972) report a mnemonist (V. P.) with a digit span of about eighteen, and his performance is attributed to a certain amount of natural ability plus massive practice in rote memorization during his upbringing in traditionalist (and sometimes textless) schools in Latvia and Germany. But, though this case illustrates the difficulties involved in using standard psychometric devices on persons from different cultures, it proves nothing about what abilities the test ordinarily measures.

Finally, the reasonably high correlation between digit span and recall on a yes-no recognition task ($r=.69$, corrected for attenuation) indicates that at least half of the variance in digit

span is independent of response organization and output strategies (experiment four). Moreover, the speed of readout of items from memory, which may or may not be under the immediate voluntary control of the subject, is unrelated to span size (experiment five).

Interpreted with reference to our theoretical framework, these results present a reasonably consistent picture; that is, each of them is evidence against the involvement of some aspect of the decision system in producing span ID's. It may be, of course, that some control process or parameter characterizing the operation of this system in the digit span task was not envisioned in our theory, and was therefore not experimentally examined. But we can think of no such process, and therefore we take the evidence to suggest that span ID's are caused by ID's in either some other processing subsystem or some general system parameter.

An example of a subsystem-specific theory which has not yet been ruled out is the notion that digit span measures an ability specific to auditory codes, whether produced directly by stimuli presented aurally, or indirectly by generating an image of the name of a visual stimulus. This theory is not necessarily inconsistent with the high correlation between visual and auditory presentation found by Brener and Jensen because enough time was available in these experiments for subjects to retrieve the names of the stimuli. Naming the items is an important aid to recall: Olsen and Furth (1965) showed that deaf adults have considerably lower digit spans than do normals, though their span for nonsense forms was

normal. Day (1973) has reported evidence that could be interpreted to be support for the importance of auditory-specific ability. She found that subjects who were classified as "fusers" because they could not adequately judge the temporal order of pairs of word fragments presented dichotically did worse on a digit recall task then did those subjects who could make the judgments. This discrimination task and others were used in a recent investigation of an attentional theory of fusion (Keele & Lyon, 1975). Fifteen of the subjects in that investigation had had digit spans assessed, and the correlation between the total errors on three auditory discrimination tasks and digit span for these subjects was -.48. If one makes the admittedly long inferential leap from skill in such tasks to a general auditory coding ability, this result is mildly suggestive.

Another subsystem which could be responsible for span ID's is the logogen system. The psychometric fact that digit span is a better indicant of verbal IQ than of performance IQ is consistent with this speculation. If span ID's could be traced to a specific parameter of the logogen system, something useful might thereby be learned about verbal ability.

An alternative view is that span ID's are caused by ID's in some general mechanism which is part of all memory processes. A decay rate parameter characterizing all activation within the brain would be one example; another would be a general acquisition parameter like the density of units available for encoding

the stimulus. Other general system parameters are listed in Table 1.

The generality of the processes involved might be assessed by examining the correlation between digit span performance and memory for unfamiliar material which would require the use of some (non-auditory) sensory representational code. A high correlation would implicate general system parameters, while a low one would argue for an ability which is specific to either auditory codes or to the logogen system.

Such an experient is not easy to do, since even unfamiliar material can be remembered via the logogen system by analyzing stimuli into familiar parts or by assimilating them into pre-existing categores. However, a pilot experiment using the probe recognition task with unfamiliar material (Hebrew letters) and fast presentation rates (three items per second) appeared to have been successful in eliminating such use of the logogen system in most subjects; only one of the thirteen subjects reported being eventually able to provide names for the letters. Most of the other subjects attempted to do so, but failed. Among these twelve subjects, the correlation between digit span and memory for Hebrew letters (corrected for attenuation) was .08.

If it can be replicated, this result would be clear evidence against the notion that span ID's are caused by general system parameters; apparently span ability may be specific to familiar materials. Yet we know from the high correlation between spans

for various familiar stimulus materials (Brener, 1940) that ID's in familiarity with digits do not underlie ID's in span size, so some more general parameter characterizing the functioning of the verbal system must be involved.

Pinpointing the exact source process or processes will require more research, guided by the theoretical structure which we have assumed. For example, the probe recognition task could be used to examine the correlation between digit span and memory for nonsense auditory material. A high correlation would localize span ID's in the auditory sensory system, while a low correlation would rule out the involvement of auditory coding parameters per se, thus implicating logogen system parameters by elimination. When the particular subsystem involved is known, more sophisticated paradigms can be used to assess particular parameter values. We feel that this investigative path, if followed carefully, will lead to a firm theoretical understanding of at least one component of intelligence.

References

Allen, R. M. The real question in digit span performance. Psychological Reports, 1962, 11, 218.

Anastasi, A. A group factor in immediate memory. Psychometric Monographs, 1930, no. 120.

Anders, T. R. Short-term memory for serially presented supraspan information in nonretarded and mentally retarded individuals. American Journal of Mental Deficiency, 1971, 73, 571-578.

Baddeley, A. D., Hatter, J. E., Scott, D., & Snashall, A. Memory and the time of day. Quarterly Journal of Experimental Psychology, 1970, 22, 605-609.

Baddeley, A. D., Thompson, & Buchannan. The word length effect and the structure of short-term memory. Paper presented at Psychonomics, Boston, 1974.

Belmont, J. M. & Butterfield, E. C. The relation of short-term memory to development and intelligence. In L. P. Lipsitt & H. W. Reese (Eds.), Advances in Child Development and Behavior. Vol. 4. New York: Academic Press, 1969.

Belmont, J. M. & Butterfield, E. C. Learning strategies as determinants of memory deficiencies. Cognitive Psychology, 1971a, 2, 411-420.

Belmon , J. M. & Butterfield, E. C. What the development of short-term memory is. Human Development, 1971b, 14, 236-248.

Blake, M. J. F. Time of day effects on performance in a range of tasks. Psychonomic Science, 1967, 9, 349-350.

Blankenship, A. B. Memory span: a review of the literature. Psychological Bulletin, 1938, 35, 1-25.

Bolton, E. Memory and intelligence. Journal of Experimental Psychology, 1931, 14, 37-67.

Brener, R. An experimental investigation of memory span. Journal of Experimental Psychology, 1940, 26, 467-482.

Brooks, L. R. Spatial and verbal components of the act of recall. Canadian Journal of Psychology, 1968, 22, 349-368.

Brown, A. L. Strategic behavior in retardate memory. In N. R. Ellis (Ed.) International Review of Research in Mental Retardation. Vol. 7. New York: Academic Press, 1974, 55-110.

Chase, W. Effects of acoustic similarity on short-term scanning. Paper presented at the meeting of the Midwestern Psychological Association, Chicago, 1974.

Chi, M. Dissertation, Carnegie-Mellon University, 1974.

Craddick, R. A. & Grossman, K. Effects of visual distraction upon performance on the WAIS light span. Psychological Reports, 1962, 10, 642.

Day, R. S. Digit span memory in language-bound and stimulus-bound subjects. Haskins Laboratory Status Report, 1973, SR-34.

Dornic, S. Some studies on the retention of order information. In P. M. A. Rabbitt & S. Dornic (Eds.), Attention and Performance V, London: Academic Press, 1975.

Easterbrook, J. A. The effect of emotion on cue utilization and the organization of behavior. Psychological Review, 1959, 66, 183-201.

Ellis, N. R. The stimulus trace and behavioral inadequacy. In N. R. Ellis (Ed.), Handbook of Mental Deficiency. New York: McGraw-Hill, 1963, 134-158.

Estes, W. K. An associative basis for coding and organization in memory. In A. W. Melton and E. Martin (Eds.), Coding Processes in Human Memory. Washington, D. C.: Winston & Sons, 1972.

Ferguson, V. Statistical Analysis in Psychology and Education. New York: McGraw-Hill, 1971.

Frank, G. H. The validity of retention of digits as a measure of attention. Journal of General Psychology, 1964, 71, 329-336.

French, J. W. The description of aptitude and achievement tests in terms of rotated factors. Psychometric Monographs, 1951, No. 5.

Galton, F. Notes on prehension in idiots. Mind, 1887, 12, 79-82.

Gilbert, J. C. Memory loss in senesence. Journal of Abnormal and Social Psychology, 1941,

Guertin, W. H. Auditory interference with digit span performance. Journal of Clinical Psychology, 1959, 15, 349.

Guilford, J. P. Psychometric Methods. New York: McGraw-Hill, 1954.

Guilford, J. P. & Hoepfner, R. The Analysis of Intelligence. New York: McGraw-Hill, 1971.

Jacobs, J. The need for a society for experimental psychology. Mind, 1886, 11, 49-54.

Jacobs, J. Experiments in "prehension". Mind, 1887, 12, 75-79.

Hockey, R. Rate of presentation in running memory and direct manipulation of input processing strategies. Quarterly Journal of Experimental Psychology, 1973, 25, 104-111.

Hodges, W. & Spielberger, C. Digit span: an indicant of trait or state anxiety? Journal of Consulting and Clinical Psychology, 1969, 33, 430-434.

Hunt, E., Frost, N., & Lunneborg, C. Individual differences in cognition: a new approach to intelligence. In G. Bower (Ed.), Advances in Learning and Motivation, Vol. 7. New York: Academic Press, 1973.

Hunt, E., Lunneborg, C., & Lewis, J. What does it mean to be high verbal? Cognitive Psychology, 1975, 7, 194-227.

Jensen, A. R. Individual differences in learning: interference factor. USOE Co-Operative Research Project No. 1867, 1964.

Jensen, A. R. A theory of primary and secondary familial retardation. In N. R. Ellis (Ed.), International Review of Research in Mental Retardation. Vol. 4. New York: Academic Press, 1970, 33-105.

Jensen, A. R. Individual differences and auditory memory. Journal of Educational Psychology, 1971, 62, 123-131.

Keele, S. W. Attention and Human Performance. Pacific Palisades, California: Goodyear, 1973.

Keele, S. W. & Lyon, D. Individual differences in word fusion: a methodological analysis. Technical Report No. 2, Center for Perceptual and Cognitive Research, University of Oregon, Eugene.

Kelley, H. P. Memory abilities: a factor analysis. Psychometric Society Monograph, 1964, No. 11.

Kleinberg, J. & Kaufman, . Constancy in short-term memory: bits and chunks. Journal of Experimental Psychology, 1971, 90, 326-333.

Knox, W. J. & Grippaldi, R. High levels of state or trait anxiety and performance on selected verbal WAIS subtests. Psychological Reports, 1970, 27, 375-379.

Luce, G. Body Time. New York: Pantheon Books, 1971.

MacKenzie, A. J. A factor analysis of modified memory span tests. Australian Journal of Psychology, 1972, 24, 19-30.

Matarazzo, J. The Measurement and Appraisal of Adult Intelligence, 1975.

Moldowsky, S. & Moldowsky, P. Digit span as an anxiety indicator. Journal of Consulting Psychology, 1952, 16, 115-118.

Morton, J. A functional model for memory. In D. A. Norman, (Ed.), Models of Human Memory. New York: Academic Press, 1970.

Norman, D. A. Cognitive organization and learning. In P. M. A. Rabbitt & S. Dornic (Eds.) Attention and Performance V, London:Academic Press, 1975.

Olsen, J. E. & Furth, H. C. Visual memory span in the deaf. American Journal of Psychology, 1966, 79, 480-484.

Pezzullo, T. R., Thorsen, E., & Madaus, G. F. The heritability of Jensen's Level I and II and divergent thinking. American Educational Research Journal, 1972, 9, 539-546.

Pollack, I., Johnson, L. B., & Knaff, P. R. Running memory span. Journal of Experimental Psychology, 1959, 57, 137-146.

Posner, M. I. Cognition: An Introduction. Glenview, IL: Scott, Foresman, 1973.

Posner, M., Klein, R., Summers, J., & Buggie, S. On the selection of signals. Memory and Cognition, 1973, 1, 2-12.

Prehm, H. J. Rote verbal learning and memory in the retarded. In H. J. Prehm, L. A. Hamerlynck, & J. E. Crosson (Eds.), Behavioral Research in Mental Retardation, University of Oregon, 1968.

Prehm, H. J., The learning deficit of the retarded: D or d? Working paper #39, Rehabilitation Research and Training Center in Mental Retardation, University of Oregon, 1970.

Pyke, S..and Agnew, N. Digit span performance as a function of noxious stimulation. Journal of Consulting Psychology, 1963, 27, 281.

Reimanis, G. & Green R. Imminence of death and intellectual decrement in the aging. Developmental Psychology, 1971, 5, 270-272.

Saunders, D. R. Digit span and alpha frequency: a cross-validation. Journal of Clinical Psychology, 1961, 17, 165-167.

Shucard, D. W. & Horn, J. L. Evoked cortical potentials and measurement of human abilities. Journal of Comparative and Physiological Psychology, 78, 59-68.

Spitz, H. H. The rôle of input organization in the learning and memory of mental retardates. In N. R. Ellis (Ed.), International Review of Research in Mental Retardation. Vol. 2 New York: Academic Press, 1968, 29-56.

Thurstone, L. L. Multiple Factor Analysis. Chicago: University of Chicago Press, 1947.

Tulving, E. Episodic and semantic memory. In E. Tulving and W. Donaldson (Eds.), Organization of Memory. New York: Academic Press, 1972, 282-402.

Wolf, T. Alfred Binet. Chicago: University of Chicago Press, 1973.

Walker, R. & Spence, J. Relationship between digit span and anxiety. Journal of Consulting Psychology, 1964, 28, 220-223.

Waugh, N. C. & Norman, D. A. Primary memory. Psychological Review, 1965, 72, 89-104.

Zimmerman, I. & Woo-Sam, J. Clinical Interpretation of the WAIS. New York: Geune & Stratton, 1973.

FOOTNOTES

[1]The split-half reliabilities are higher ($\sqrt{r_{55}r_{55}}$=.94); using them yields a corrected slow-fast correlation of .87.

[2]Reliabilities for these scores are, unfortunately, unavailable.

[3]Split-half reliabilities are as follows:

mean readout rate: .69

mean 6-5 score: .90

mean reaction time: .97

[4]Split-half reliability of B_2 is .70; the reliability of B_1 is less satisfactory (r=.58).